Magnetic Anisotropy Adjusted Laminated Magnetic Thin Films for Magnetic Recording

5   Field of the Invention

The invention relates to magnetic thin film media with laminated magnetic layers and also to magnetic thin film media with laminated magnetic layers that have one or more antiferromagnetically coupled layer structures included therein and

10   more particularly to magnetic properties and selection of materials used for the plurality of thin films in such media.

Background of the Invention

15   A typical prior art head and disk system 10 is illustrated in block form in Figure 1. In operation the magnetic transducer 20 is supported by the suspension 13 as it flies above the disk 16. The magnetic transducer 20, usually called a "head" or "slider," is composed of elements that perform the task of writing magnetic transitions (the write head 23) and reading the magnetic

20   transitions (the read head 12). The electrical signals to and from the read and write heads 12, 23 travel along conductive paths (leads) 14 which are attached to or embedded in the suspension 13. The magnetic transducer 20 is positioned over points at varying radial distances from the center of the disk 16 to read and write circular tracks (not shown). The disk 16 is attached to a spindle 18 that is

25   driven by a spindle motor 24 to rotate the disk 16. The disk 16 comprises a substrate 26 on which a plurality of thin films 21 are deposited. The thin films 21 include ferromagnetic material in which the write head 23 records the magnetic transitions in which information is encoded.
       The conventional disk 16 includes substrate 26 of glass or AlMg with an

30   electroless coating of Ni_3P that has been highly polished. The thin films 21 on the disk 16 typically include a chromium or chromium alloy underlayer and at

least one ferromagnetic layer based on various alloys of cobalt. For example, a commonly used alloy is CoPtCr. Additional elements such as tantalum and boron are often used in the magnetic alloy. A protective overcoat layer is used to improve wearability and corrosion resistance. Various seed layers, multiple

5   underlayers and laminated magnetic films have all been described in the prior art. The laminated magnetic films have included multiple ferromagnetic layers that are separated by nonmagnetic spacer layers and more recently antiferromagnetic coupling has been proposed. It is known that substantially improved SNR can be achieved by the use of a laminated magnetic layer

10   structure. The reduced media noise is believed due to reduced exchange coupling between the magnetic layers. The use of lamination for noise reduction has been extensively studied to find the favorable spacer layer materials, including Cr, CrV, Mo and Ru, and spacer thicknesses from a few Angstroms upward that result in the best decoupling of the magnetic layers and the lowest

15   media noise.

       In U.S. patent 6,280,813 to Carey, et al. a layer structure is described that includes at least two ferromagnetic films antiferromagnetically coupled together across a nonferromagnetic coupling/spacer film. In general, it is said that the exchange coupling oscillates from ferromagnetic to antiferromagnetic with

20   increasing coupling/spacer film thickness and that the preferred 6 Angstrom thickness of the ruthenium coupling/spacer layer was selected because it corresponds to the first antiferromagnetic coupling peak in the oscillation for the particular thin film structure. Materials that are appropriate for use as the nonferromagnetic coupling/spacer films include ruthenium (Ru), chromium (Cr),

25   rhodium (Rh), iridium (Ir), copper (Cu), and their alloys. Because the magnetic moments of the two antiferromagnetically coupled films are oriented antiparallel, the net remanent magnetization-thickness product (M_rt) of the recording layer is the difference in the M_rt values of the two ferromagnetic films. This reduction in M_rt is accomplished without a reduction in the thermal stability of the recording

30   medium because the volumes of the grains in the antiferromagnetically coupled films add constructively. An embodiment of the structure includes two

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ferromagnetic CoPtCrB films, separated by a Ru spacer film having a thickness

selected to maximize the antiferromagnetic exchange coupling between the two

CoPtCrB films. The top ferromagnetic layer is designed to have a greater $M_r t$

than the bottom ferromagnetic layer, so that the net moment in zero applied

5   magnetic field is low, but nonzero. The Carey '813 patent also states that the

antiferromagnetic coupling is enhanced by a thin (5 Angstroms) ferromagnetic

cobalt interface layer added between the coupling/spacer layer and the top

and/or bottom ferromagnetic layers. The patent mentions, but does not elaborate

on the use CoCr interface layers.

10   In U.S. patent 6567236 to Doerner, et al., titled "Antiferromagnetically

Coupled Thin Films for Magnetic Recording," an antiferromagnetically coupled

layer structure for magnetic recording wherein the top ferromagnetic structure is

a bilayer structure including a relatively thin first sublayer of ferromagnetic

material in contact with the coupling/spacer layer. The first sublayer has a higher

15   magnetic moment than the second sublayer. The second sublayer has a lower

magnetic moment and is much thicker than the first sublayer with a composition

and thickness selected to provide the $M_r t$ when combined with first sublayer that

is needed for the overall magnetic structure.   A preferred embodiment of a layer

structure according to the patent is a pre-seed layer preferably of CrTi; a seed

20   layer preferably of RuAl; an underlayer preferably of CrTi; a bottom ferromagnetic

layer preferably of CoCr; an antiferromagnetic coupling/spacer layer preferably

of Ru; and a top ferromagnetic structure including: a thin first sublayer of

material preferably of CoCr, CoCrB or CoPtCrB, and a thicker second sublayer of

material preferably of CoPtCrB with a lower moment than the first sublayer.

25   As the storage density of magnetic recording disks has increased, the

product of the remanent magnetization M_r (the magnetic moment per unit volume

of ferromagnetic material) and the magnetic layer thickness t has decreased.

Similarly, the coercive field or coercivity (H_c) of the magnetic layer has increased.

This has led to a decrease in the ratio $M_r t$ / H_c. To achieve the reduction in $M_r t$,

30   the thickness t of the magnetic layer can be reduced, but only to a limit because

the layer will exhibit increasing magnetic decay, which has been attributed to

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thermal activation of small magnetic grains, i.e. the superparamagnetic effect. The thermal stability of a magnetic grain is to a large extent determined by K_uV, where K_u is the magnetic anisotropy constant of the layer and V is the volume of the magnetic grain. As the layer thickness is decreased, V decreases. At some

5   point, as V decreases, the stored magnetic information will no longer be stable under the storage device's operating conditions.

One approach to the solution of this problem is to use a higher anisotropy material, i.e. one with a higher K_u. However, the increase in K_u is limited by the point where the coercivity H_c, which is approximately equal to K_u/M_r, becomes

10   too great to be written by a practical write heads. A similar approach is to reduce the M_r of the magnetic layer for a fixed layer thickness, but this is also limited by the coercivity that can be written. Another solution is to increase the intergranular exchange, so that the effective magnetic volume V of the magnetic grains is increased. However, this approach has been shown to be deleterious to the

15   intrinsic signal-to-noise ratio (SNR) of the magnetic layer.

Substantially improved SNR can be achieved by replacing a single magnetic layer with a laminated magnetic layer stack of two (or more) magnetic layers separated by nonmagnetic spacer layers. The reduction in media noise by lamination is believed due to a decoupling of the magnetic exchange coupling

20   between the magnetic layers in the laminate. Spacer layer materials, including Cr, CrV, Mo and Ru, with thicknesses, from 5 to 400 A have been reported to achieve good decoupling of the magnetic layers. Even a discontinuous chromium film has been claimed to reduce the exchange coupling between the two magnetic layers.

25   Published US patent application 2002/0098390 describes a laminated medium for horizontal magnetic recording that includes an antiferromagnetically (AF)-coupled magnetic layer structure and a conventional single magnetic layer. The AF-coupled magnetic layer structure has a net remanent magnetization-thickness product (M_rt) which is the difference in the M_rt values of its two

30   ferromagnetic films. The type of ferromagnetic material and the thickness values of the ferromagnetic films are chosen so that the net moment in zero applied field

will be low, but nonzero. The $M_r t$ for the media is given by the sum of the $M_r t$ of the upper magnetic layer and the $M_r t$ of the AF-coupled layer stack.

The convention for alloy composition used in this application gives the atomic percentage of an element as a subscript; for example, $CoCr_{10}$ is 10 atomic percent Cr with balance being Co and $CoPt_{11}Cr_{20}B_7$ is 11 atomic percent Pt, 20 atomic percent Cr and 7 atomic percent B with the balance being Co.

Summary of the Invention

One embodiment of the invention is a laminated magnetic recording medium comprising two magnetic layers separated by a nonmagnetic spacer layer with the lower magnetic layer, i.e., the one farther away from the recording head, having a lower magnetic anisotropy than the upper magnetic layer that is closer to the recording head. In alternative embodiments of the invention one or both of the two magnetic layers in the laminated layer stack can be replaced with an antiferromagnetically (AF) coupled (AFC) layer structure that has an AFC-master and an AFC-slave layer separated by a spacer layer selected to antiferromagnetically couple the AFC-master and AFC-slave layers. In embodiments with one or more AFC layer structures the AFC-slave layers are ignored when adjusting the anisotropy according to the invention. For example, in an embodiment that has the lower magnetic layer replaced with an AF-coupled layer structure, the AFC-master magnetic layer is adjusted to have a lower magnetic anisotropy than the upper magnetic layer. Because the recording head field is reduced with increased distance from the head, selection of the magnetic layers according to the invention helps to respectively match the magnetic anisotropy of the relevant magnetic layer with the head field exerted on it. This matching allows the magnetic layers to be written under optimum conditions by the head at the same head write current. Magnetic media made according to the invention show a single sharp peak in the DC erase noise vs. head write current plot which indicates that the magnetic transitions in the non-slave magnetic

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layers are written (switch) at the same head write current, leading to the improved magnetic recording performance. In comparison, media using the same magnetic material for both the upper and AFC-master magnetic layers shows double peaks in the DC erase noise vs. head write current plot, indicating an

5   unfavorable write condition in which the two magnetic layers are switched at different head write current. The benefits of the invention are that magnetic pulse width (PW_{50}) is reduced, overwrite (OW) is improved and media signal-to-noise ratio (S_oNR) is improved.   In one embodiment the upper magnetic layer is selected as a high magnetization alloy so that a thinner layer can be used to

10   achieve the same M_rt and further improve overwrite.

Brief Description of the Figures

Figure 1 is a symbolic illustration of the prior art showing the relationships

15   between the head and associated components in a disk drive.

Figure 2 is an illustration of a prior art layer structure for a magnetic thin film disk with which the magnetic layer stack of the invention can be used.

20   Figure 3 is an illustration of a two layer laminated magnetic layer stack for a magnetic thin film disk according to the invention.

Figure 4 is an illustration of a laminated magnetic layer stack with the lower magnetic layer replaced with an antiferromagnetically coupled magnetic layer

25   stack for a magnetic thin film disk according to the invention.

Figure 5 is a graph of normalized DC erase noise vs. head write current for Disk 4 with magnetic materials selected according to the invention.

30   Figure 6 is a graph of normalized DC erase noise vs. head write current for a disk using the same magnetic material for both the upper and the AFC-master

magnetic layers (similar to Disk 2) according to the prior art.

Detailed Description of the Invention and the Preferred Embodiments

Figure 2 illustrates a prior art layer structure 21 of a thin film magnetic disk 16 in which the layer stack according to the invention can be used. The layers under the underlayer 33 may be any of several combinations of seed layers 32 and pre-seed layers 31 as noted in more detail below. Useful pre-seed layers include but are not limited to CrTi, CrTiAl or CrTiY. Seed layers are typically used on nonmetallic substrates, but the invention can also be used with metallic substrates such as NiP-coated AlMg. Conventionally NiP-coated AlMg substrates are used with an underlayer structure of Cr, Cr alloy or multiple Cr and Cr alloy layers which are sputter deposited directly onto the NiP. The invention is also not dependent on any particular underlayer being used.

The layer structure shown in Figure 2 can be used with a variety of magnetic layer stacks 34. For example, two or more laminated magnetic layers can be used and antiferromagnetically coupled layers structures can be substituted for any or all of the magnetic layers. One embodiment of the magnetic layer stack 34 is composed of a plurality of layers which are further illustrated in Figure 3. A first embodiment of a layer stack 34 according to the invention is a laminated structure including an upper magnetic layer 36 (the magnetic layer nearest to the surface of the disk and, therefore, the head), a spacer layer 37 and a lower magnetic layer 38. The material for the lower magnetic layer 38 is selected to have a lower magnetic anisotropy than the upper magnetic layer 36. The magnetic anisotropy can be adjusted primarily by changing the atomic percentage of platinum in a cobalt based magnetic alloy such as CoPtCr, CoPtCrTa or CoPtCrB. A higher atomic percentage of platinum yields higher magnetic anisotropy. Chromium and boron content may also affect

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magnetic anisotropy of the magnetic material. Generally lower chromium and/or boron content result in higher magnetic anisotropy. It is preferable, although not required, to use material with high magnetization as the upper magnetic layer to achieve the same $M_r t$ at lower thickness to further improve **OW**. The

5   magnetization can be adjusted by altering the atomic percentage of chromium and/or boron. For example, lowering chromium and/or boron content and increasing the cobalt content will increase the magnetization.

        A second embodiment of the layer stack 34 is illustrated in Figure 4. As noted above an antiferromagnetically coupled layer structure can be substituted

10   for any or all of the magnetic layers in a laminated layer stack. The embodiment in Figure 4 has an antiferromagnetically coupled layer structure 41 substituted in place of the lower magnetic layer 38 of Figure 3. An antiferromagnetically coupled layer structure 41 according to the invention has at least three distinct layers with the magnetic layers antiferromagnetically coupled through the

15   nonmagnetic spacer layer. The two magnetic layers of the antiferromagnetically coupled layer structure 41 will be referred to as AFC-master magnetic layer 42 for the upper one and AFC-slave magnetic layer 44 for the lower one. Each of these layers is a ferromagnetic material of the type used in the prior art of thin film disks. Examples of materials suitable include CoCr, CoCrB, CoCrTa,

20   CoPtCr, CoPtCrTa and CoPtCrB. The thickness of the AFC-slave magnetic layer 44 must be chosen so that its $M_r t$ is lower than that of the AFC-master magnetic layer 42. The AFC spacer layer 43 is a nonmagnetic material with a thickness that is selected to antiferromagnetically couple the AFC-master magnetic layer 42 with the AFC-slave magnetic layer 44. Ruthenium is the preferred material for

25   the coupling/spacer layer 43, but the prior art indicates that suitable materials include chromium (Cr), rhodium (Rh), iridium (Ir), copper (Cu), and their alloys. The thickness of the AFC spacer layer 43 is according to the prior art; for example, approximately 6 Angstroms is a preferred target thickness for a ruthenium AFC spacer layer 43. The upper magnetic layer 36 according to the

30   invention is a ferromagnetic material having a higher magnetic anisotropy than AFC-master magnetic layer 42. The recording head field is reduced with

increase of distance from the head. Consequently, at a given head write current the head field exerted on the AFC-master magnetic layer is weaker than that on the upper magnetic layer. Therefore, in order to respectively match the magnetic anisotropy of the relevant magnetic layer with the head field exerted on it, the

5   AFC-master magnetic layer needs to have lower magnetic anisotropy than the upper magnetic layer. The difference in the magnetic anisotropy of the two magnetic layers depends on the characteristics of head field reduction with distance. The upper magnetic layer also preferably has high magnetization.

In an alternative embodiment the upper magnetic layer 36 can be replaced

10   with an AF-coupled layer structure 41. The layers for this embodiment are the same as shown in Figure 4 except that AF-coupled layer structure is on top. In this alternative embodiment the lower magnetic layer 38 has a lower magnetic anisotropy than the AFC-master magnetic layer 42. The AFC-master magnetic layer preferably has high magnetization.

15   In an alternative embodiment the upper magnetic layer 36 and the lower magnetic layer 38 can be respectively replaced with two AF-coupled layer structures 41. In this alternative embodiment the AFC-master magnetic layer in the AF-coupled structure replacing lower magnetic layer 38 has a lower magnetic anisotropy than the AFC-master magnetic layer in the AF-coupled structure

20   replacing upper magnetic layer 36. The AFC-master magnetic layer in the AF-coupled structure replacing upper magnetic layer 36 preferably has high magnetization.

Tables 1-5 compare nine experimental disks two at a time to isolate differences resulting from a change in a single characteristic. The media

25   structure is that shown in Figures 2 and 4. The materials for each of the layers are shown in the caption or in the body of the table for each of the test disks. The $K_u V/kT$ value is for the complete media. Each of the disks has a pre-seed layer of $CrTi_{50}$ and a seed layer of $RuAl_{50}$. Table 1 compares two disks with different alloys for the AFC-master magnetic layer 42 in an antiferromagnetically

30   coupled magnetic layer stack 34 as illustrated in Figure 4. Disk 1 has an AFC-master magnetic layer with lower magnetic anisotropy ($CoPt_{11}Cr_{20}B_7$) than the

upper magnetic layer ($CoPt_{12}Cr_{14}B_{11}$). The AFC-master magnetic layer and the upper magnetic layer in Disk 2 are made from the same material ($CoPt_{12}Cr_{14}B_{11}$). The thickness of the AFC-master magnetic layer in Disk 1 is adjusted so that Disk 1 has similar thermal stability to Disk 2 as indicated by their **K_uV/kT** values

5 (Disk 1 = 73; Disk 2 = 74). The fact that the two disks have similar thermal stability shows that the improved recording performance of Disk 1 over Disk 2 has not been achieved by sacrificing thermal stability. The results show that Disk 1 is improved over Disk 2 in that **OW** is higher by 3.5dB, **PW_{50}** is lower by 3.9nm at even higher amplitude and **S_oNR** is higher by 0.9dB.

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Table 1

$CrTi_{50}/RuAl_{50}/underlayer/CoCr_{10}/Ru/$ AFC-master magnetic layer$/Ru/CoPt_{12}Cr_{14}B_{11}$

	AFC-master Magnetic Layer	**H_c** (Oe)	**M_rt** **(memu/cm^2)**	**S_oNR**	**OW** (dB)	**PW_{50}** (nm)	**LFTAA** (mv)	**K_uV/kT**
DISK 1	$CoPt_{11}Cr_{20}B_7$	3762	0.65	31.0	25.4	123.4	1.560	73
DISK 2	$CoPt_{12}Cr_{14}B_{11}$	3998	0.69	30.1	21.9	127.3	1.362	74

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The data in Table 2 compare Disk 1 with Disk 3. Disk 3 has an upper magnetic layer with a higher magnetization than that of Disk 1, but is otherwise the same. Disk 3 has 0.4 dB **OW** better than Disk 1 and its thermal stability with

20 **K_uV/kT** equal to 76 is even higher than that of Disk 1 (**K_uV/kT** =73). Disks 1-3 all have an underlayer of $CrTi_{10}$. Disks 4-7 use $CrTi_{20}$ for the underlayer which helps to reduce **PW_{50}** at increased amplitude.

Table 3 illustrates the applicant's finding that the **OW** of the laminated AF-coupled media can be improved by thinning the AFC-master magnetic layer to a

certain extent without significantly affecting thermal stability. Table 3 compares disks 4 and 6 which differ in the thickness of their AFC-master magnetic layer and, therefore, $M_r t$. Disk 6 which has the thinner AFC-master magnetic layer has 1.2dB higher **OW** than Disk 4 with only one unit reduction in $K_u V/kT$.

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Table 2

$CrTi_{50}/RuAl_{50}/underlayer/CoCr_{10}/Ru/CoPt_{11}Cr_{20}B_7$ /Ru/ upper magnetic layer

	Upper Magnetic Layer	H_c (Oe)	$M_r t$ (memu/cm^2)	S_oNR	OW (dB)	PW_{50} (nm)	LFTAA (mv)	$K_u V/kT$
DISK 3	$CoPt_{12}Cr_{16}B_9$	3850	0.65	30.9	25.8	124.2	1.566	76
DISK 1	$CoPt_{12}Cr_{14}B_{11}$	3762	0.65	31.0	25.4	123.4	1.560	73

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Table 3

$CrTi_{50}/RuAl_{50}/CrTi_{20}/CoCr_{10}/Ru/CoPt_{11}Cr_{20}B_7$ (Mrt varied) /Ru/CoPt$_{12}$Cr$_{16}$B$_9$

	$M_r t$ (memu/cm^2) AFC-master Magnetic Layer	H_c (Oe)	$M_r t$ (memu/cm^2)	S_oNR	OW (dB)	PW_{50} (nm)	LFTAA (mv)	$K_u V/kT$
DISK 6	0.34	3594	0.64	26.3	25.7	125.6	1.884	75
DISK 4	0.38	3674	0.67	26.2	24.5	127.8	1.982	76

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Table 4

CrTi$_{50}$/RuAl$_{50}$/ CrTi$_{20}$/CoCr$_{10}$/Ru/CoPt$_{11}$Cr$_{20}$B$_7$ /Ru/ upper magnetic layer

	Upper Magnetic Layer	H$_c$ (Oe)	M$_r$t (memu /cm^2)	AC Squeeze	S$_o$NR	OW (dB)	PW$_{50}$ (nm)	LFTAA (mV)	K$_u$V/kT
DIS K 7	CoPt$_{13}$Cr$_{19}$B$_7$	3736	0.58	53.8	26.9	25.5	119.2	1.476	75
DIS K 6	CoPt$_{12}$Cr$_{16}$B$_9$	3594	0.64	48.4	26.5	25.5	120.4	1.606	75

Table 4 compares Disk 6 with Disk 7 to show that increased anisotropy of the upper magnetic layer reduces side band erase. Disk 7 which uses the higher anisotropy upper magnetic layer (CoPt$_{13}$Cr$_{19}$B$_7$) has higher AC squeeze which leads to reduction in the width of the side erase band. Thermal stability and **OW** of Disk 7 are maintained at the same level as disk 6 due to the changes in **M$_r$t** and **H$_c$**.

The **OW** of the laminated AF-coupled disk structure according to the invention can be further improved by using a thinner Ru upper spacer layer 41 between the upper and AFC-master magnetic layers. Tables 5 and 6 show that the **OW** is increased by 1dB when the upper space layer thickness is reduced from 1.2nm (Disk 9) to 0.8nm (Disk 8).

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Table 5

$CrTi_{50}/RuAl_{50}/ CrTi_{20}/CoCr_{10}/Ru/CoPt_{11}Cr_{20}B_7$ /Ru(thickness varied)/ $CoPt_{13}Cr_{19}B_7$

	Ru thickness (nm)	H_c (Oe)	$M_r t$ (memu/cm^2)	S_oNR	OW (dB)	PW_{50} (nm)	LFTAA (mv)
DISK 8	0.8	3694	0.58	27.7	23.7	118.6	1.476
DISK 9	1.2	3712	0.58	27.5	22.7	118.3	1.606

Table 6

$CrTi_{50}/RuAl_{50}/ CrTi_{20}/CoCr_{10}/Ru/CoPt_{11}Cr_{20}B_7$ /Ru(thickness varied)/ $CoPt_{12}Cr_{20}B_6$

Ru thickness (nm)	OW (dB)
0.6	28.1
0.8	28.1
1.0	27.5
1.2	27.1

As discussed earlier, Disk 4 selects magnetic materials with different magnetic anisotropy according to the invention to respectively match the magnetic anisotropy of the relevant magnetic layer with the head field exerted on it. As a result, a single sharp peak is observed in the normalized DC erase noise vs. head write current plot (Figure 5), which indicates that the magnetic switching of both the upper magnetic layer and the AFC-master magnetic layer occurs at the same head write current, leading to the improved magnetic recording performance. In comparison, a prior art disk using the same magnetic material

for both the upper and AFC-master magnetic layers (similar to Disk 2) shows double peaks in the normalized DC erase noise vs. head write current plot (Figure 6), indicating an unfavorable write condition in which the two magnetic layers are switched at different head write current. This measurement can be used to adjust the magnetic anisotropy. For example, the peak at the lower head write current in the graph of Figure 6 corresponds to the switching point of the magnetic layer closest to the head, i.e., the upper magnetic layer. Therefore, to bring the switching of the lower magnetic layer, i.e., the AFC-master magnetic layer, more in line with the upper magnetic layer, the magnetic anisotropy of the AFC-master magnetic layer should be lowered which will allow it to switch at a lower head write current. Tuning using the DC erase noise is a useful technique, but the actual recording performance measurements as discussed above can also be used.

The thin film structures described above can be formed using standard sputtering techniques. The films are sequentially sputter deposited with each film being deposited on the previous film. The atomic percent compositions given above are given without regard for the small amounts of contamination that invariably exist in sputtered thin films as is well known to those skilled in the art.

The invention has been described with respect to particular embodiments, but other uses and applications for the ferromagnetic structure according to the invention will be apparent to those skilled in the art.

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